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TECHNICAL REPORT ARCCB-TR-94003

A REVIEW OF WELDMENT FAILURE MODES AND WELDABILITY TESTING METHODS

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JANUARY 1994

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
January 1994

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
A REVIEW OF WELDMENT FAILURE MODES
AND WELDABILITY TESTING METHODS

5. FUNDING NUMBERS
AMCMS No. 6126.24.H180.000
PRON No. 1A12ZW22NMBJ

6. AUTHOR(S)
George Young

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, SMCAR-CCB-TL
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER
ARCCB-TR-94003

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

Accession For

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DTIC TAB	☐
Unannounced	☐
Justification	

By
Distribution /

Availability Codes

Dist	Avail and / or Special
A-1	

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

An engineering study was conducted that reviewed typical weldment failure modes and the types of weldability test procedures currently used to predict behavioral response of a material that is to be welded. In comparing the design effectiveness of these tests, each has certain inherent technical advantages/disadvantages associated with it. The tests, if used appropriately, can save untold time and costs associated with poorly welded structures/components that fail in service prematurely. They are divided into two major categories, direct and indirect, related to the test methodology or procedure used to generate results. Specifically, direct tests make use of actual weldments, while indirect tests utilize basic metallurgical principles to predict weld behavior. From this study, it should be apparent that determining what the most appropriate weldability test procedure is for obtaining useful results for a given situation is critical to the success of that test.

DTIC QUALITY INSPECTED 3

14. SUBJECT TERMS
Weldability, Hot Cracking, Cold Cracking, Heat-Affected Zone

15. NUMBER OF PAGES
23

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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INTRODUCTION

With the catastrophic failure of many Liberty ships during World War II, the phenomenon of weldment cracking and the question of weldability were brought into the forefront of metallurgical engineering (ref 1). An example of one of those ships that failed is the S.S. Schenectady, which split in two at her outfitting dock (ref 2). The ensuing investigation into these ship failures extended beyond the quality of the actual welded joints to encompass numerous factors, including environment, operating conditions, and residual stress considerations. The multiplicity of this study is an important illustration of how the definition of weldability must encompass more than just the mechanical quality of the welded joint. Additional factors to be considered include the effects of environment, fatigue, and stress corrosion. Weldability, then, is a qualitative term which may be defined as the ease at which a satisfactory joint is produced relative to a range of service conditions.

Weldability studies generally differentiate between hot cracking and cold cracking phenomena. Hot cracking is a term associated with the fracture of solidifying weld metal, while cold cracking encompasses failure of the solidified weldment. Note that these tests may encompass additional variables such as the effect of environment on hot cracking.

Weldability tests may be classified into two broad categories, direct and indirect tests. Direct weldability tests make use of an actual weldment on the service material, while indirect tests utilize basic metallurgical principles to examine the effects of welding variables on the final product. Direct weldability tests are of greatest practical importance to the engineer and designer because they are designed to closely approximate actual production welds and welding conditions. While more removed from actual fabrication conditions, indirect weldability tests provide valuable metallurgical information that may be impractical or impossible to obtain through direct methods.

Weldability testing offers an economical and rational way to investigate the effects of chemistry, welding parameters, material, and weld processes on the quality of the actual weldment. In order to be effective, a weldability test should provide (ref 3):

- Information that has direct relevance to a production weld
- Sensitivity to the effect of welding variables
- A high degree of reproducibility
- Simplicity of operation

Certain weldability tests are quantified by a characteristic parameter. These include the *Nil Ductility Temperature* (NDT), defined as the temperature at which a material loses the ability to deform plastically and fails by fast fracture, and the *Fracture Appearance Transition Temperature* (FATT), defined as the temperature at which fracture of the weld changes from a ductile to a brittle manner. Note that the FATT is generally specified as a percent of a given type of fracture, e.g., the temperature at which the fracture surface appears to be 50 percent ductile. Other parameters include the *Fracture Transition for Elastic Loading* (FTE) and the *Fracture Transition for Plastic Loading* (FTP). The FTE is defined as the temperature below which a fracture will propagate into the elastically loaded area at the edge of the specimen, and the FTP is the temperature above which the fracture is arrested in the plastically deformed region of the specimen (ref 3).

As most weldability tests investigate the cracking behavior of a weldment, the precise classification of the type of cracking occurring is of importance. Definitions of common types of cracking failure encountered in welding are as follows:

Hot Cracking - Hot cracking is the type of cracking that occurs at the liquid/solid interface of a weld and is caused by both grain boundary liquation (hot shortness) and solidification stresses (see Figure 1). Hot cracking is promoted by chemical segregation effects of low melting constituents. These low melting constituents, such as sulphur and copper, tend to aggregate in the last metal to solidify, thus forming a weak plane within the weldment (ref 4). The metallurgical phenomenon of liquid metal embrittlement is closely associated with hot cracking.

Hydrogen Cracking - Hydrogen cracking is commonly referred to as cold cracking. It is influenced by four factors: hydrogen in the weld metal, high applied or residual stresses, susceptible microstructure (e.g., martensite), and relatively low temperature (ref 5). Figure 2 shows a good example of hydrogen cracking in a fillet weld of 1040 steel. Preheating a specimen prior to welding often alleviates hydrogen cracking by slowing the cooling rate of the specimen, thus allowing more time for hydrogen gas to diffuse from the weldment.

Lamellar Tearing - Lamellar tearing is a type of cracking caused by a combination of high localized stresses (usually caused by thermal contraction), low ductility of the base metal, and the presence of nonmetallic inclusions parallel to the rolling direction of the base metal (ref 5). Tearing is initiated at the weak inclusion/metal interface and usually occurs in or near the heat-affected zone of the weldment (see Figure 3).

Reheat Cracking - Reheat cracking generally occurs in the heat-affected zone of a weld during reheating (i.e., a stress-relieving operation) as a result of residual stresses (ref 5). Figure 4 shows an example of reheat cracking.

Solidification Cracking - Solidification cracking is an intergranular type of fracture that occurs during cooling when the stresses developed across solidifying, adjacent grains exceed the strength of partially solidified weld metal. Solidification cracks may appear as open tears, or may "backfill," commonly with low melting constituents of the weldment (ref 5).

DIRECT TESTS

Cracking in base or weld metal caused by thermal stresses is termed restraint cracking. Restraint tests analyze hot cracking by varying the amount of restraint a weld experiences, while the cooling effect associated with the mass of the specimen is held constant (ref 3). Originally designed as a test to determine the hot cracking sensitivity of a base material, the varestraint test has been used to study (ref 6):

- The hot cracking sensitivity of filler metals
- The effect of alloying elements on hot cracking behavior
- The basic mechanisms of hot cracking

The varestraint test apparatus is illustrated in Figure 5. Note that subscale specimens have also been used (ref 7). The basic procedure for testing is as follows:

- An arc is struck and travels left to right along the test specimen using the appropriate process, geometry, and welding parameters.
- As the arc passes point A, the loading yoke bends the specimen suddenly downward to conform to the curvature of the die block B.
- The arc travels int' area C and is terminated.

The test specimen is then visually examined in the as-welded and as-polished conditions. The three criteria used to evaluate the test are:

1. Cracking threshold - the minimum augmented strain needed to cause cracking
2. Total crack length - the sum of the lengths of all the cracks present
3. Maximum crack length - the length of the longest crack

Variations on the varestraint test include the spot varestraint test (or Tigmajig), the Sigmajig, and the transvarestraint tests (refs 1,7). As the name implies, the spot varestraint test utilizes a spot weld rather than a weld bead to investigate heat-affected zone and liquation cracking (see Figure 6). The Sigmajig test is designed for thin sheet weldability testing. In the transvarestraint test (Figure 7), a transverse strain is applied to the specimen rather than a longitudinal strain.

The Lehigh restraint test was developed to quantify the degree of restraint at which cracking occurs in butt welds (ref 3). The critical restraint is expressed numerically as a function of distance X, shown in Figure 8. Cracking is detected visually as-welded, or by examining a cross section taken at the midpoint of the specimen and ground to a 50 grit finish. Magnetic particle inspection may also be used in inspecting cross sections. The Lehigh restraint test has been used to determine the effects of the following variables on restraint cracking:

- Hydrogen content
- Base metal composition
- Heat input
- Electrode variables
- Preheat
- Prior microstructure

Another useful restraint test, the tapered fin test, may be used to study the resistance to both crack initiation and crack growth (ref 3). If the weld bead is struck at point A in Figure 9, and travels along line AB until a crack initiates, the test gauges the material's sensitivity to crack initiation. Conversely, if the bead is struck near point B, initiating a crack, and travels along line BA until cracking ceases, the test measures the material's crack growth resistance. Note that a similar test, the Houldcroft restraint test, was developed for weldability testing of sheet gauge steels (ref 3). Figure 10 is a schematic of the Houldcroft test specimen. Other restraint-type tests include the keyhole and the circumferential-weld restraint tests.

Bending tests evaluate welds by applying a bending moment across a weld joint or heat-affected zone. These tests are categorized into free bend and guide bend types of tests. Free bend tests are used to determine weld joint ductility, while guide bend tests evaluate the soundness of the welded joint (ref 8).

Figures 11a and 11b are schematics of the free bend test apparatus showing initial bend fixturing and final bend fixturing, respectively. After initial bending, the specimen is placed on the final bend fixture and bent until a specified flaw size (commonly 1/16 inch) is produced. Ductility is measured as the percent elongation of two reference marks.

Impact tests such as the drop-weight test and the explosion-bulge test determine an important weldability parameter, the NDT. Although the exact definition of this parameter may change with each test, it is essentially the temperature at which the material loses the ability to deform plastically (ref 3).

Figure 12 is a schematic of the drop-weight test. Note that this test may also be classified as a bending-type test. The drop-weight test has been augmented by the drop-weight-tear test, which utilizes a notched specimen.

The explosion-bulge test was developed to simulate military-type, high loading rates on the specimen. When performed over a temperature range, a characteristic NDT may be established. Note that both notched and unnotched specimens may be used as well as a slotted specimen (i.e., the explosion-tear test) (ref 3).

INDIRECT TESTS

Fundamental to weldability determination is a metallurgical understanding of the materials to be welded. The physical metallurgical structure of the base material, filler metal, and the final product are vital elements in predicting the ease of joining and the quality of the final welded structure. Metallurgical characterization may include:

- Hardness testing
- Metallography
- Chemical analysis
- Electron microscopy
- Mechanical testing

The Gleeble apparatus (see Figure 13) essentially consists of a load cell equipped with special grips capable of quickly heating and cooling the test specimen. The capability of thermal cycling allows weld heat-affected zones to be simulated. The Gleeble apparatus has also been used to investigate elevated temperature ductility, thermal expansion, and low-cycle thermal fatigue. Note that Gleeble techniques are not limited to tensile loading (ref 3).

The cast-pin-tear test was developed to investigate supersolidus cracking. Essentially, the test consists of levitation melting small amounts of metal in an inert gas atmosphere, and casting the melts into tapered pin-shaped copper molds. As the solidifying melt contracts and the copper mold expands, a tensile stress is applied to the ends of the pins. Figure 14 is a schematic of the cast-pin-tear test apparatus.

SUMMARY

As was evident from the catastrophic failure of many Liberty ships during World War II, the phenomenon of weldment cracking is of tremendous engineering importance. One manner in which weldment quality can be investigated is through weldability testing techniques. Weldability testing offers an economic and scientific way of studying the effects of numerous factors on the quality of the final weldment. Direct testing methods, which utilize an actual weld on service material, offer the closest correlation to a production weld, while indirect tests may reveal information impossible to obtain by direct methods. Direct testing methods can be subdivided into restraint, bend, and impact types of tests. Restraint tests investigate the effect of strain on hot cracking behavior, bend tests quantify weld ductility, and impact tests generally determine a characteristic temperature where the fracture mode of the weldment changes. Augmenting direct tests, indirect testing methods help characterize a weldment by providing important metallurgical information that is difficult or impossible to obtain through direct testing methods.

REFERENCES

1. R.G. Baker, R.E. Dolby, and F. Watkinson, "The Assessment of Cracking Problems," *Weldability of Structural and Pressure Vessel Steels, Conference Proceedings - Volume I, The Papers,* The Welding Institute, Cambridge, U.K., 1970.

2. *The Design and Methods of Cons.. uction of Welded Steel Merchant Vessels*, U.S. Government Printing Office, Washington, D.C., 19...

3. Robert D. Stout and W. O'Orville Doty, *Weldability of Steels*, Welding Research Council, New York, 1978.

4. V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures*, John Wiley & Sons, New York, 1974.

5. Sindou Kou, *Welding Metallurgy*, John Wiley & Sons, New York, 1987.

6. W.F. Savage and C.D. Lundin, *Application of the Varestraint Technique to the Study of Weldability*, Welding Research Supplement, 1966.

7. W.A. Baeslack, S. Ernst, and J.C. Lippold, "Weldability of High Strength, Low-Expansion Superalloys," Edison Welding Institute, Columbus, OH, June 1988.

8. Boniface E. Rossi, *Welding Engineering*, McGraw-Hill, New York, 1954.

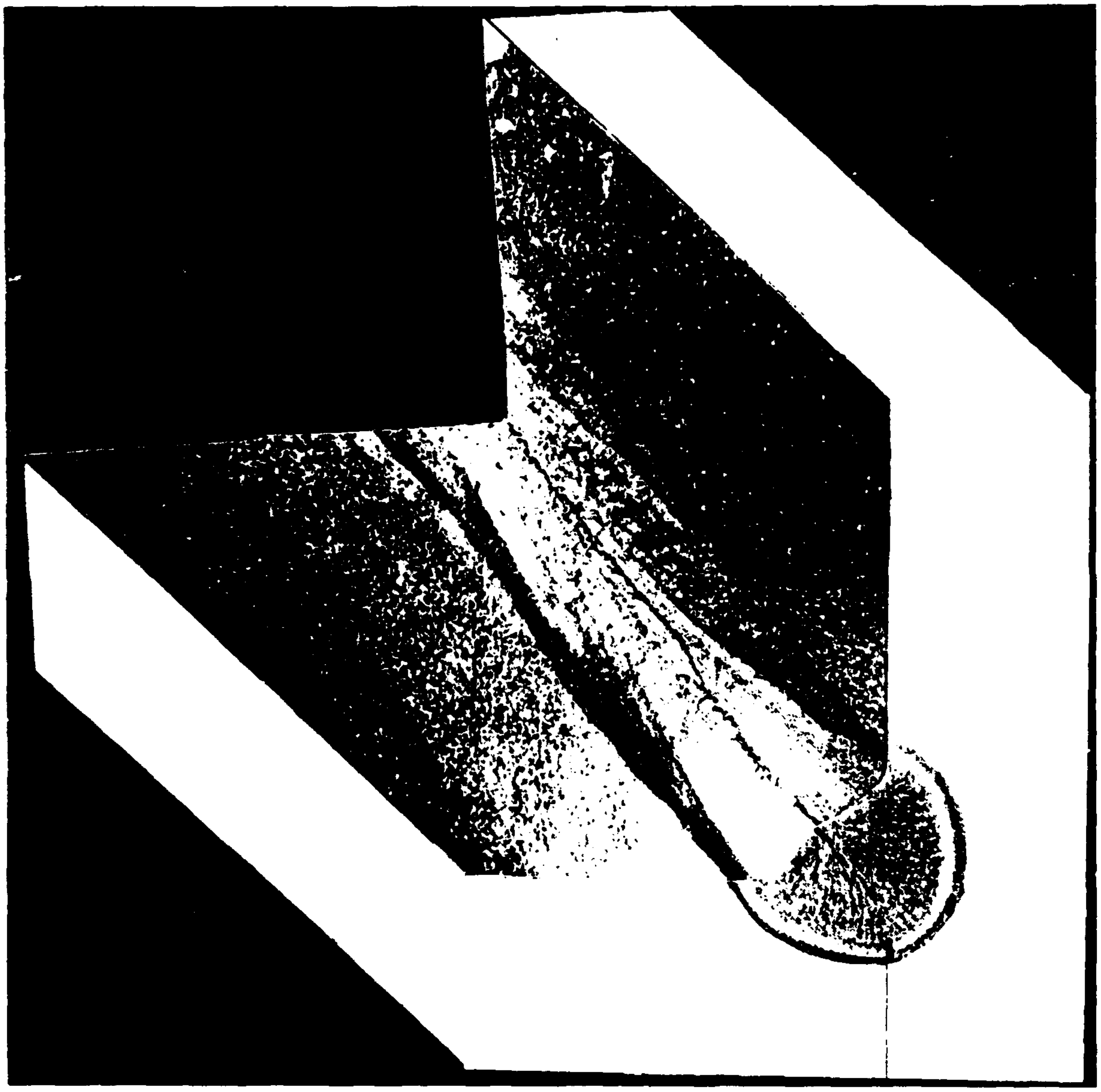
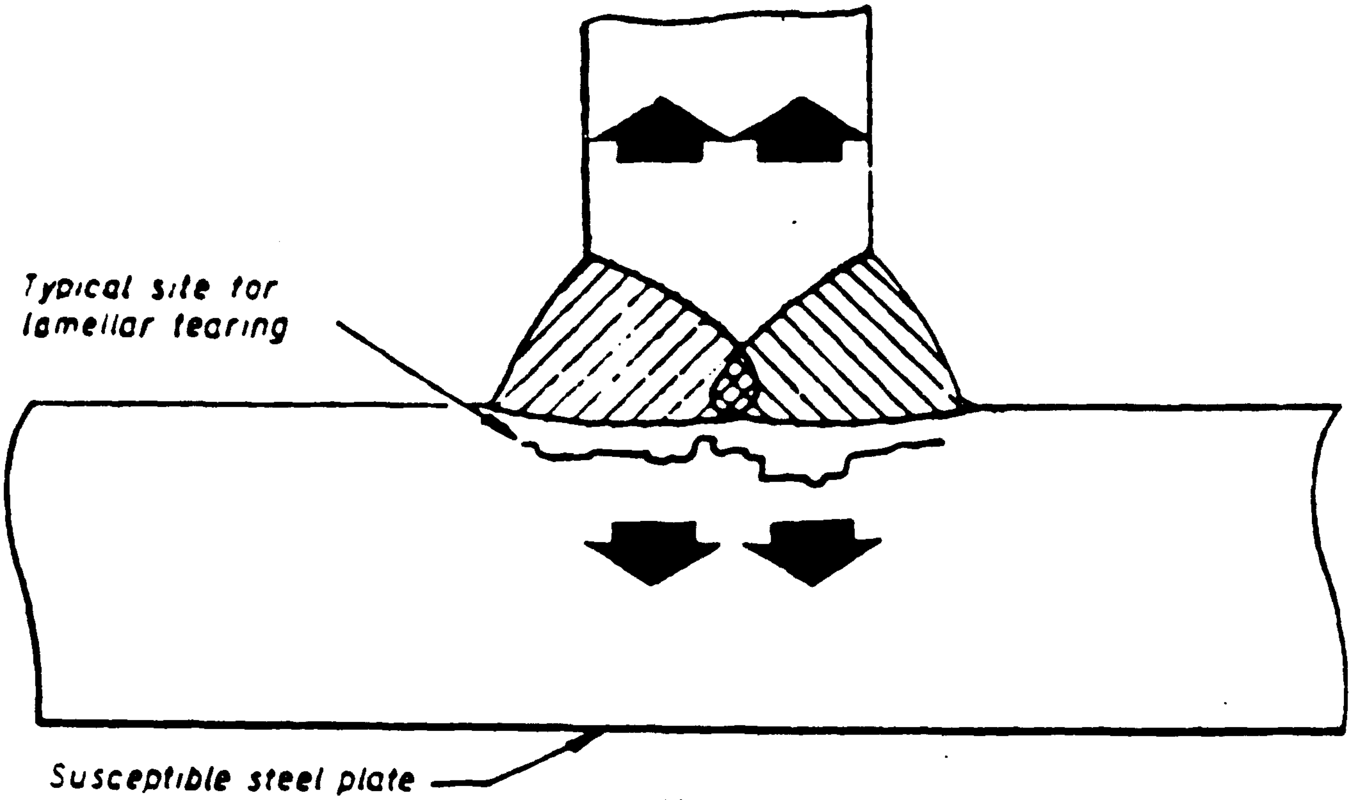


Figure 1. An example of hot cracking in a fillet weld.

(a) Macrograph.

(b) Micrograph of crack and martensitic microstructure.

Figure 2. Hydrogen cracking in a fillet weld of 1040 steel.



(a)

(b)

Figure 3. Schematic and microstructure of lamellar tearing.

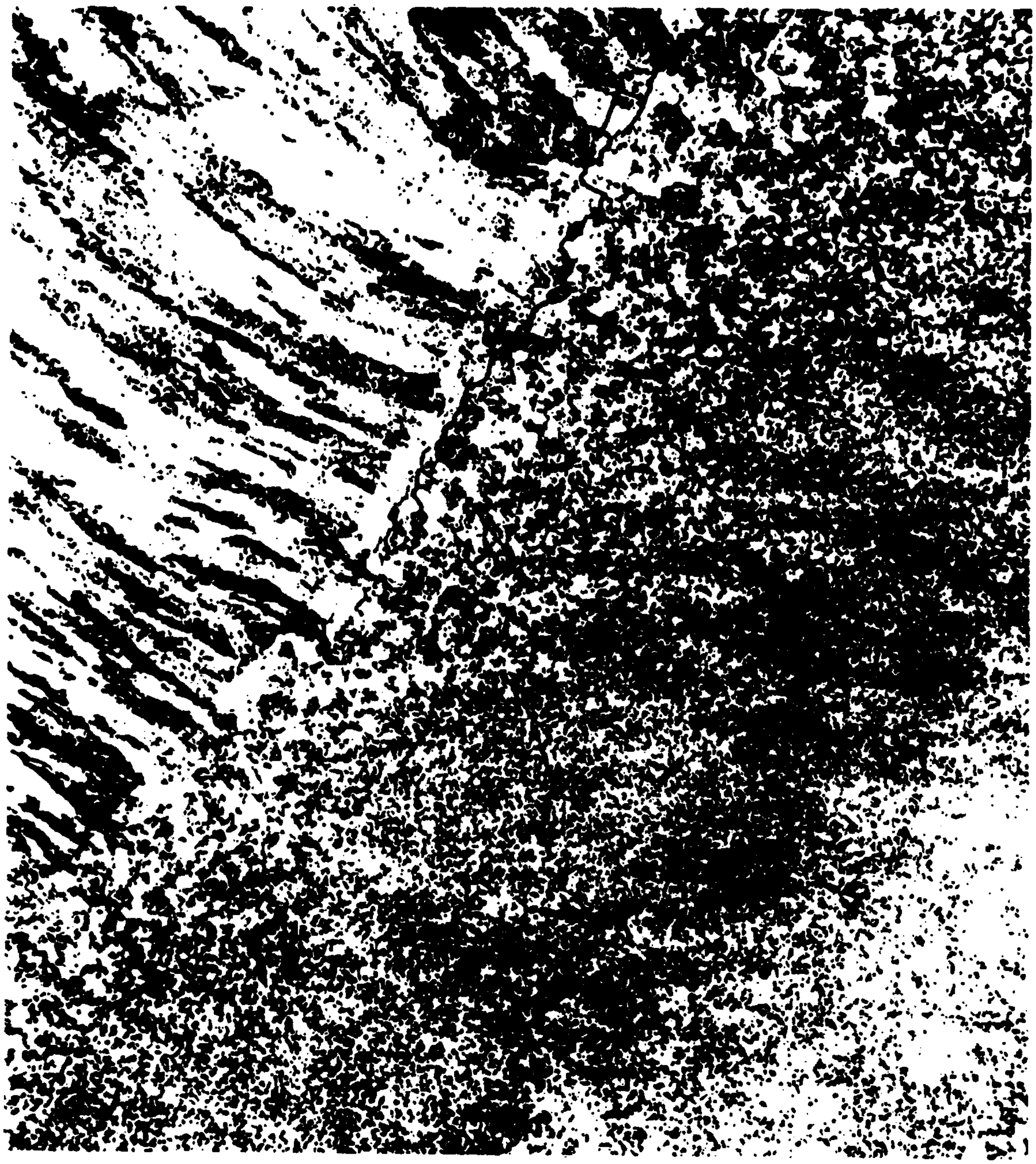


Figure 4a. Macrostructure of reheat cracking in a chromium-molybdenum-vanadium steel.

Figure 10. Microstructure showing cracks along prior austenitic grain boundaries

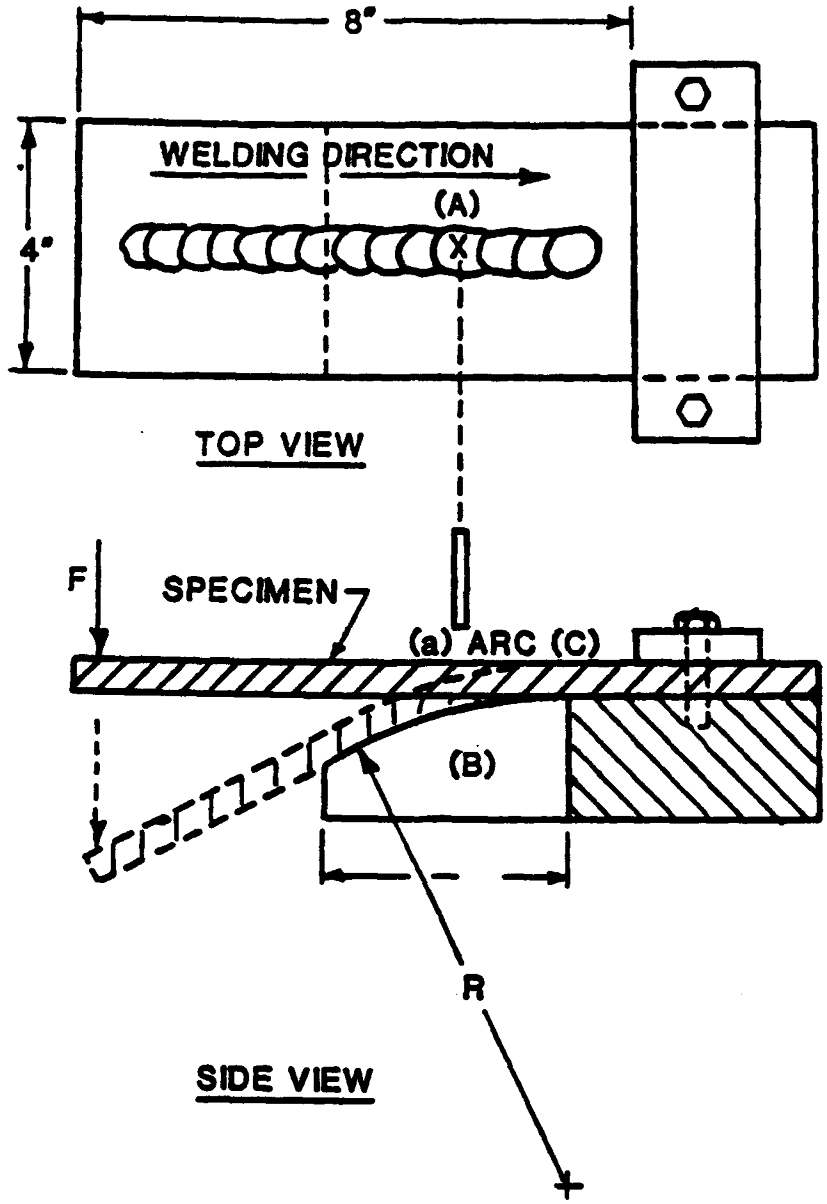


Figure 5. Schematic of the subscale varestraint test.

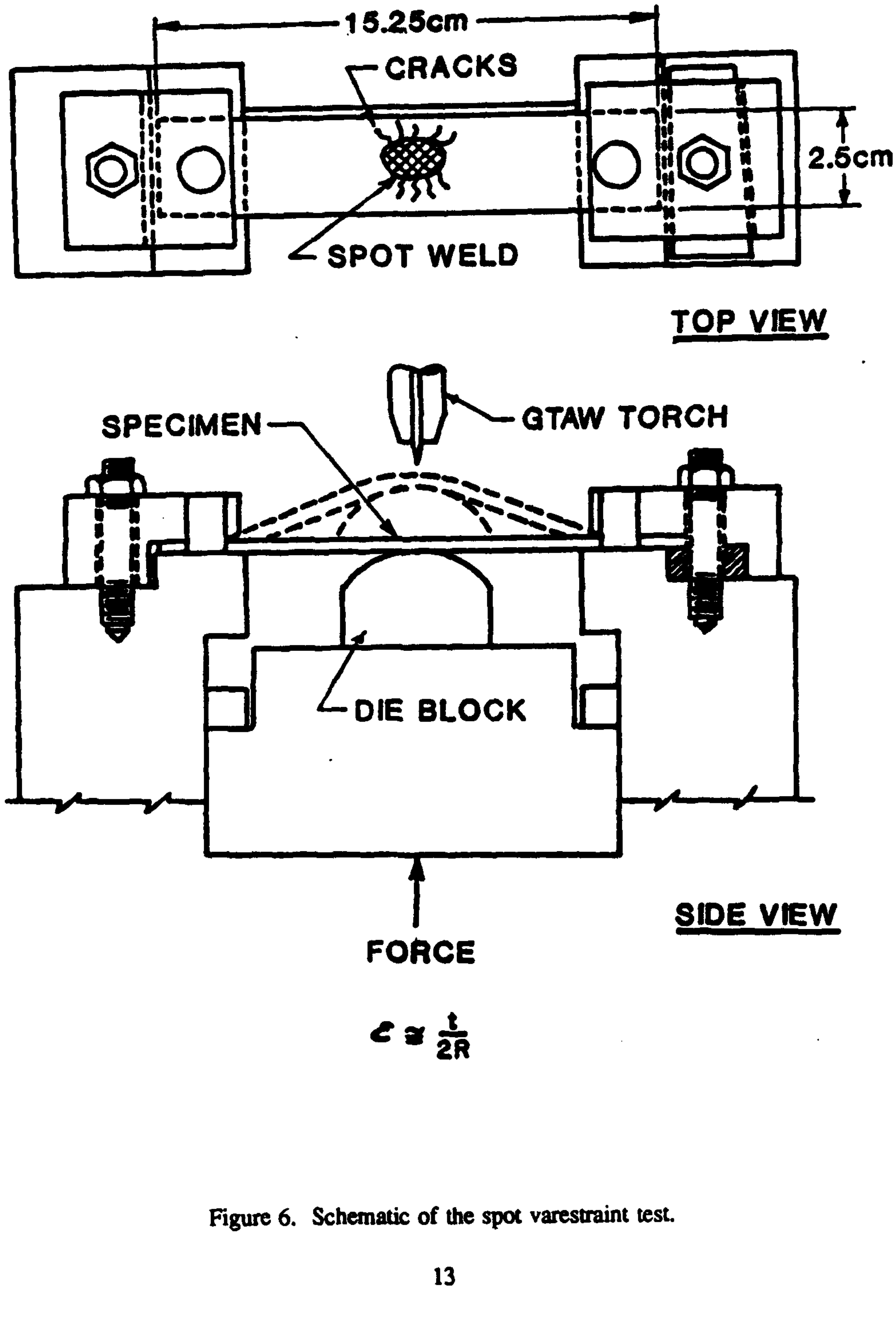


Figure 6. Schematic of the spot varestraint test.

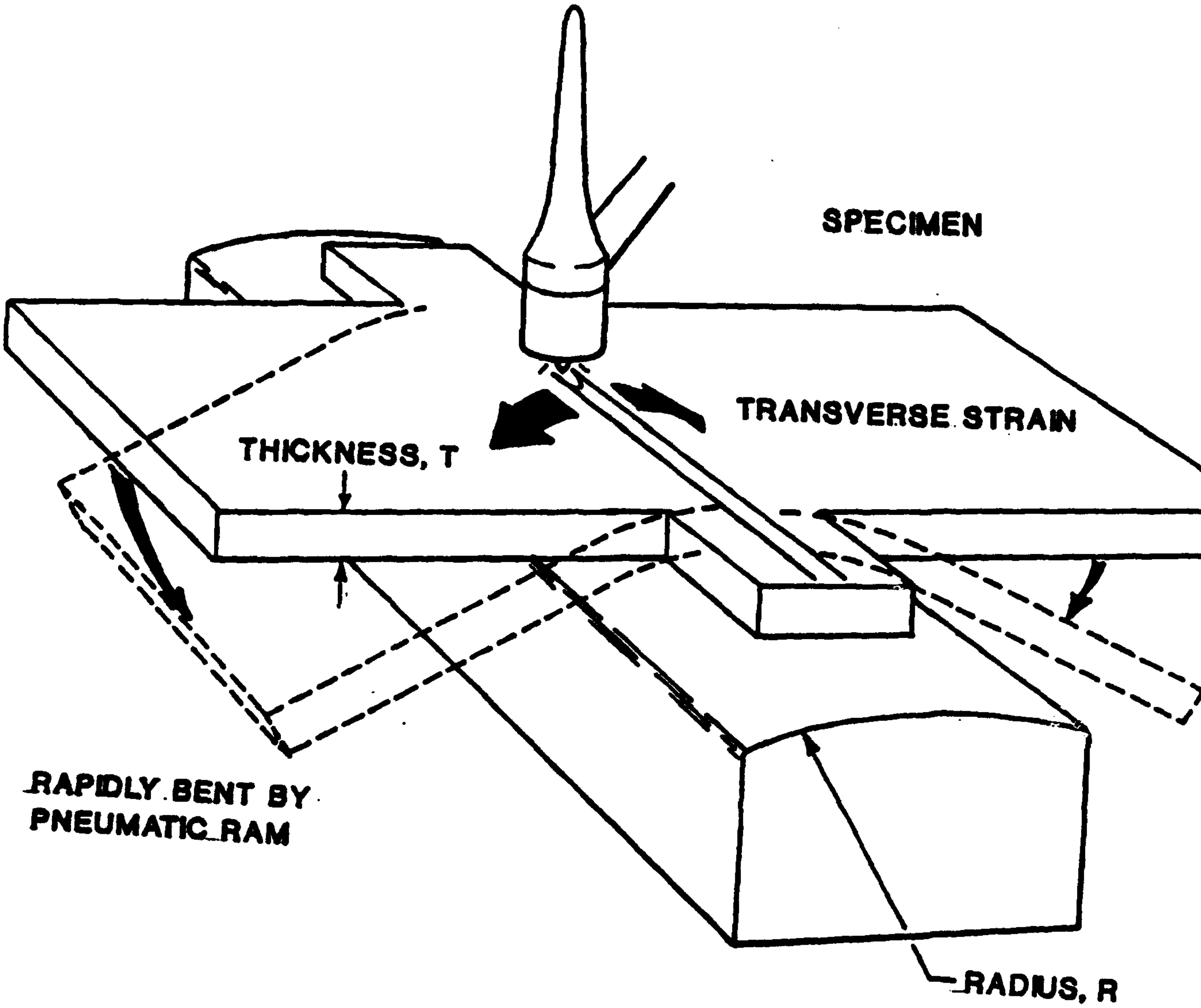


Figure 7. Schematic of the transvarestraint test.

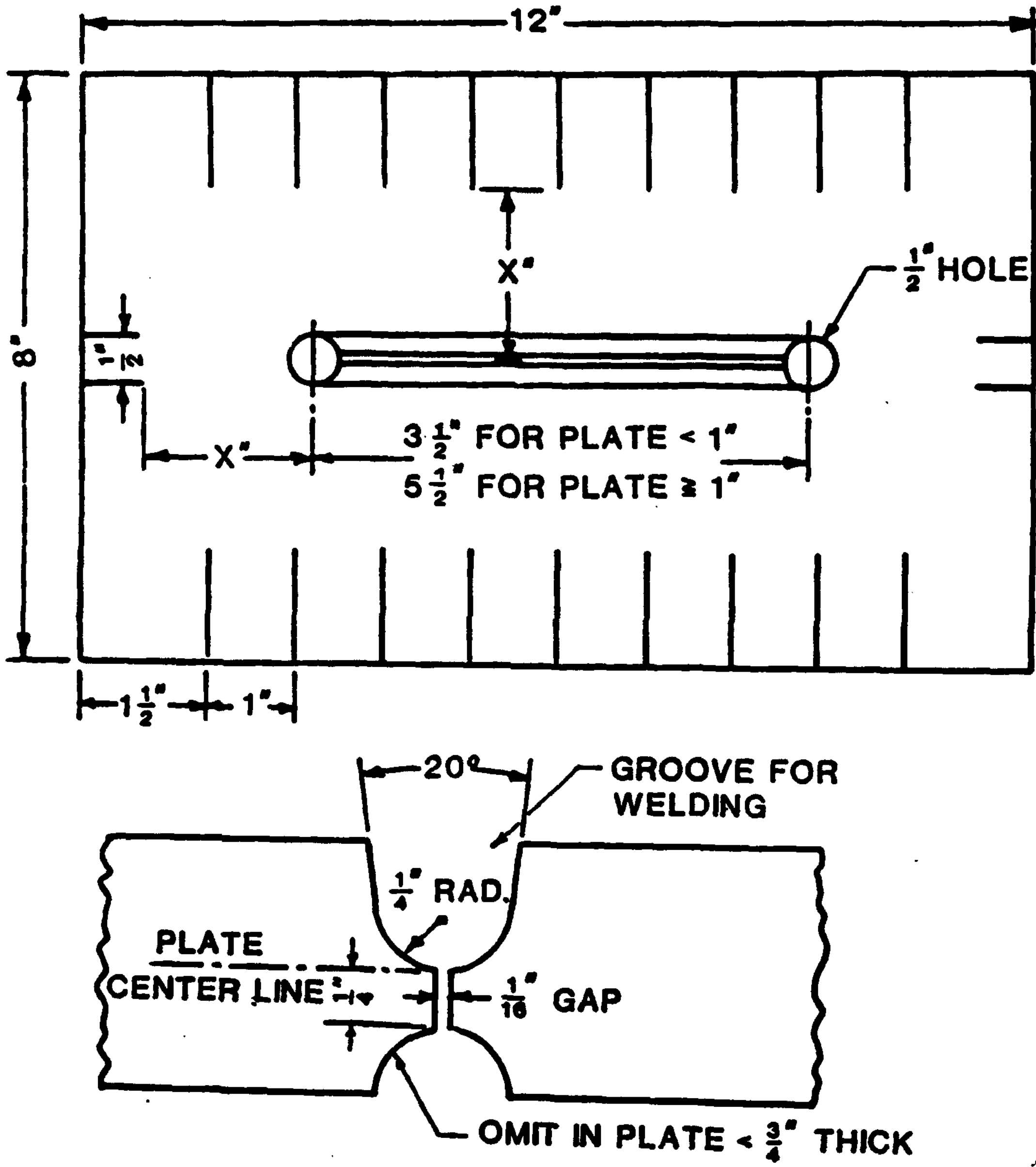


Figure 8. Schematic of the Lehigh restraint test specimen.

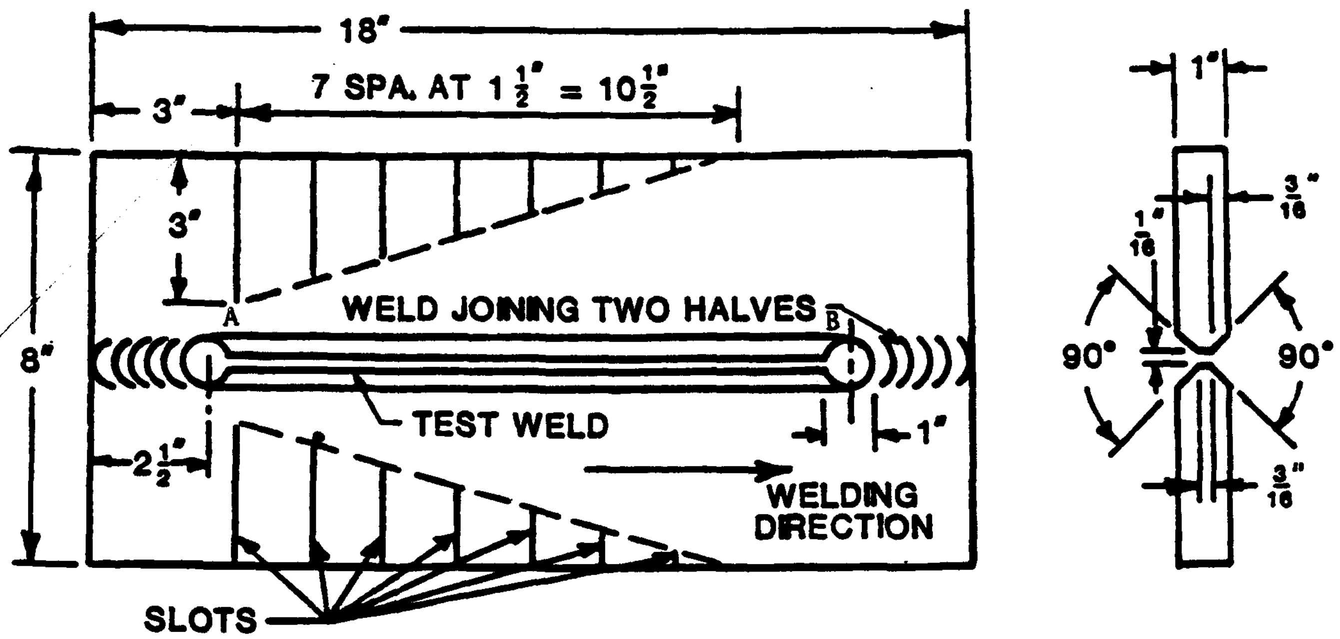


Figure 9. Schematic of the tapered fin test specimen.

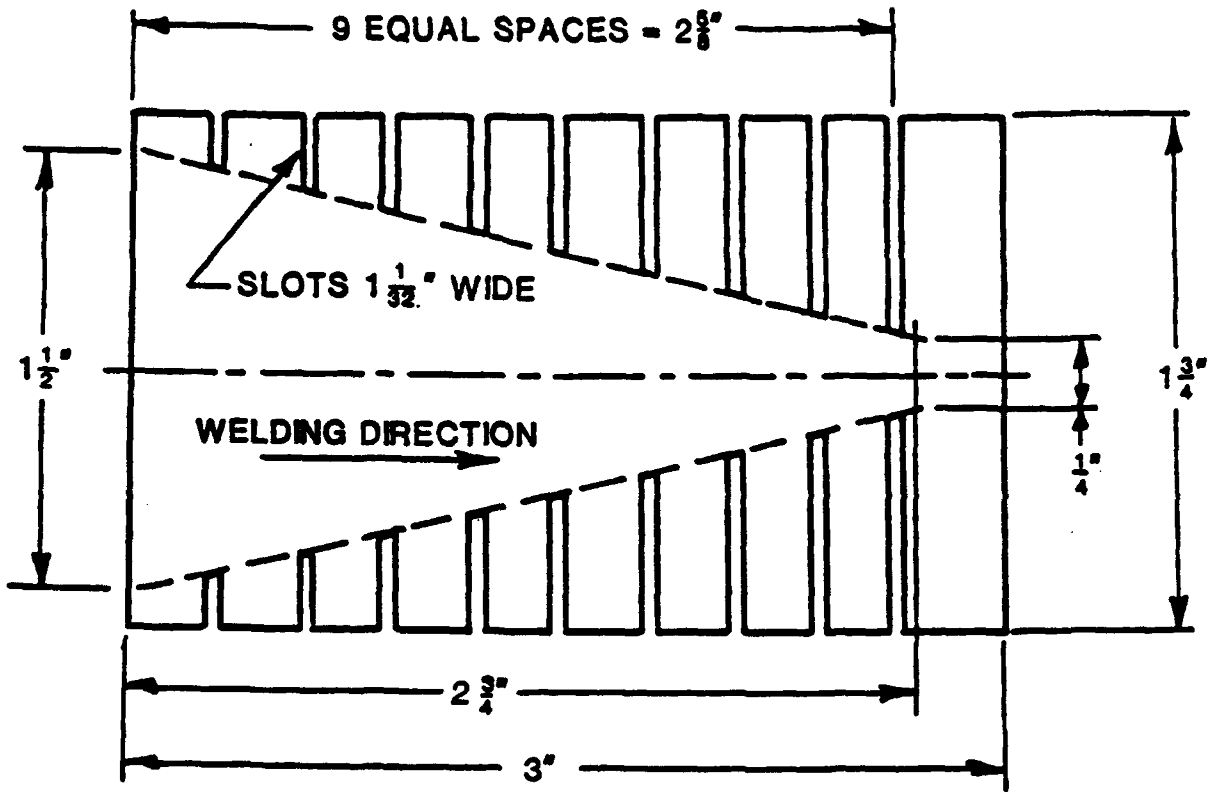


Figure 10. Schematic of the Houldcroft test specimen.

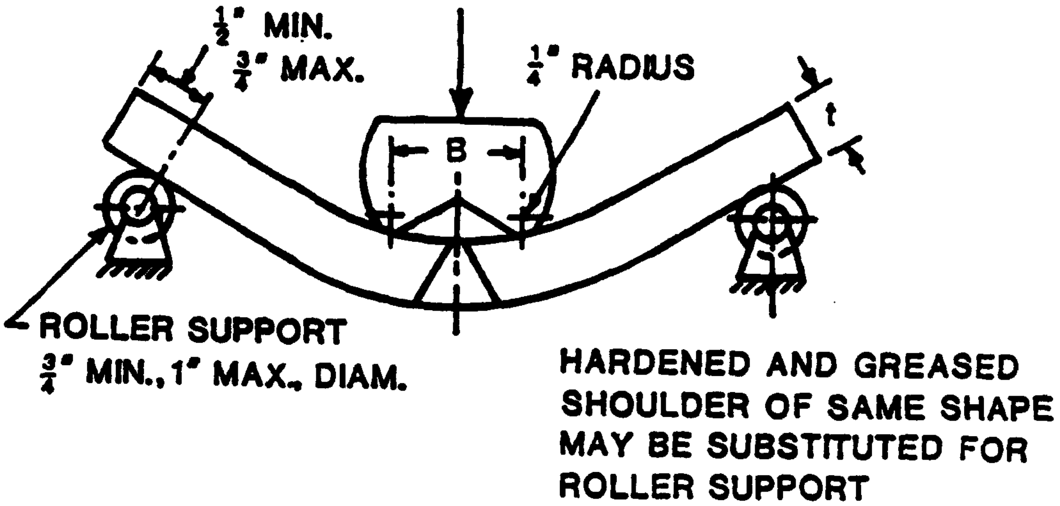


Figure 11a. Schematic of free bend test apparatus showing initial bend fixturing.

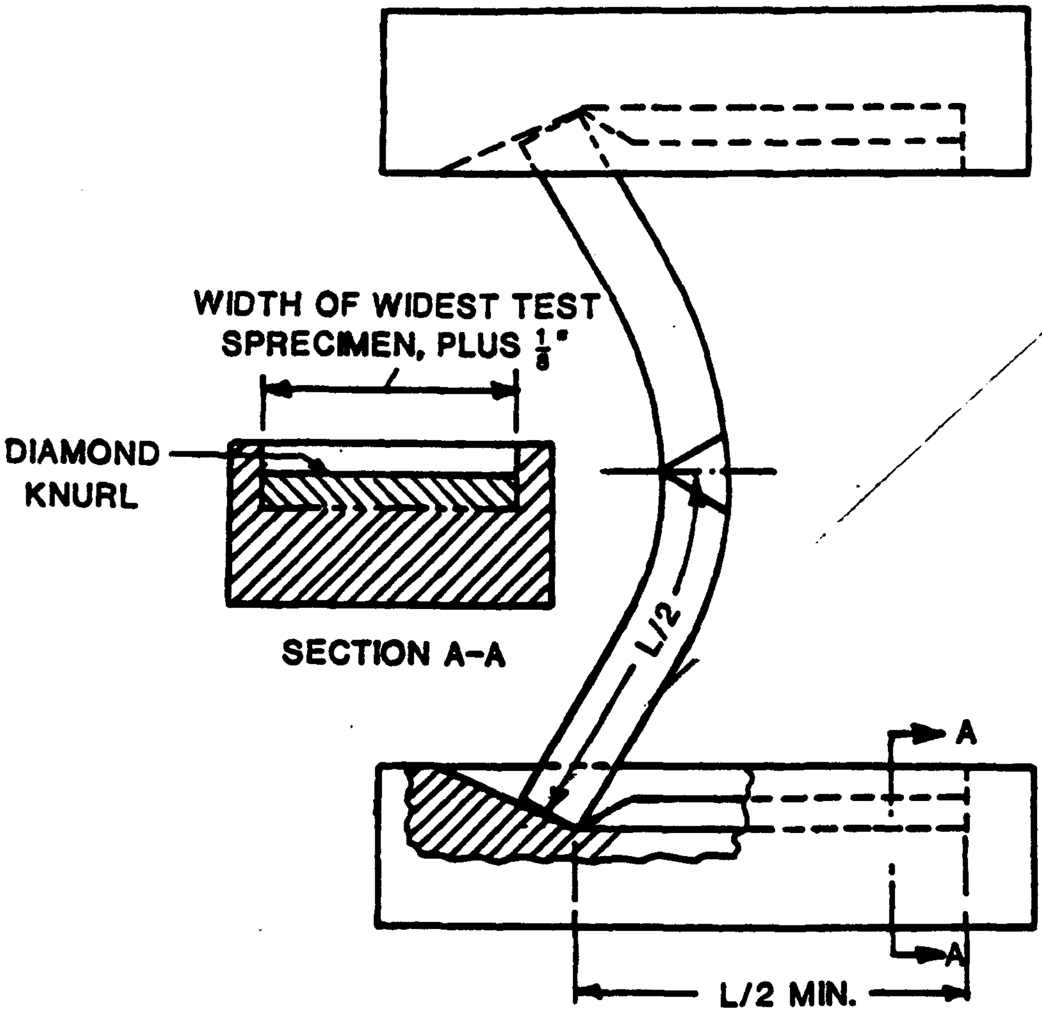


Figure 11b. Schematic of free bend test apparatus showing final bend fixturing.

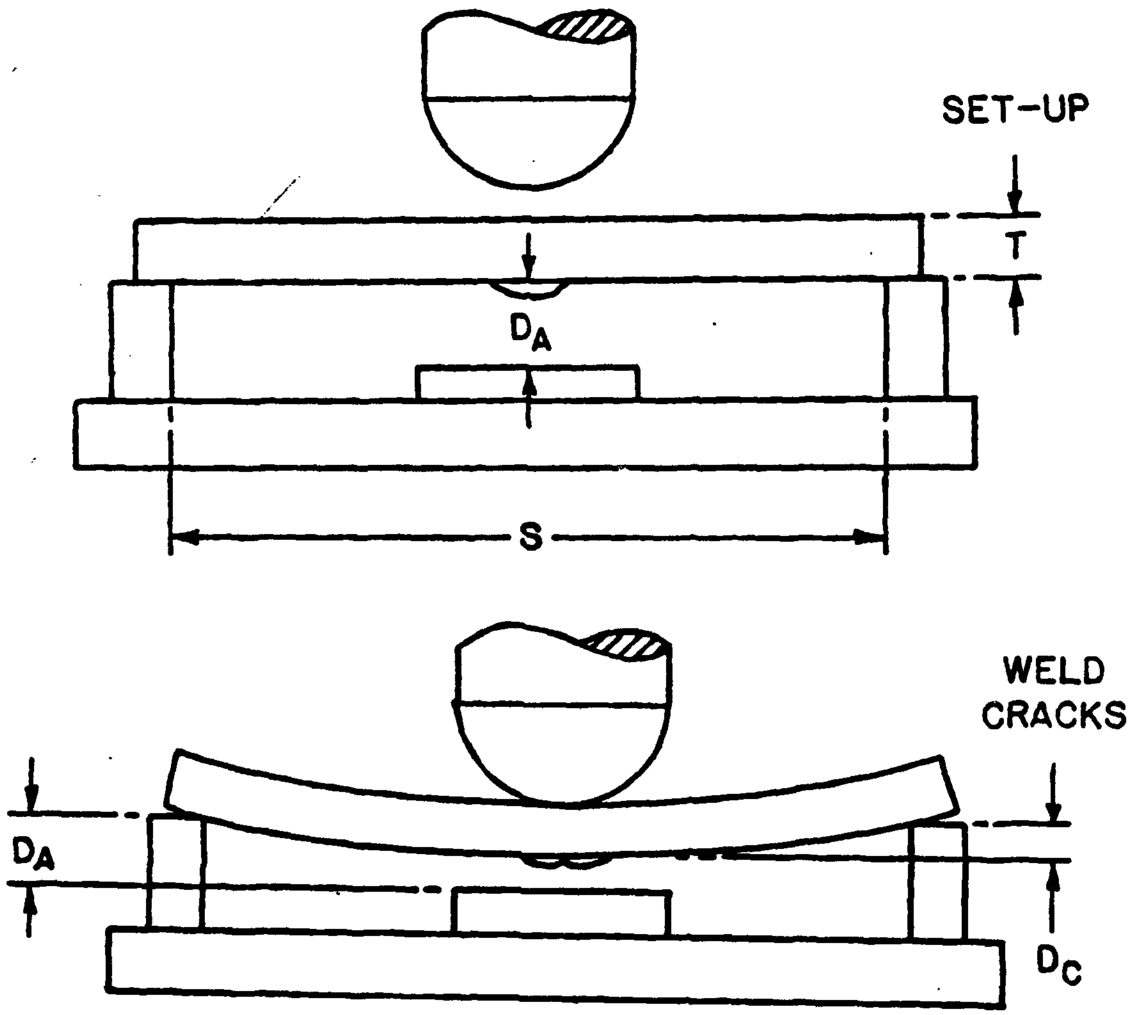


Figure 12. Schematic of the drop-weight test.

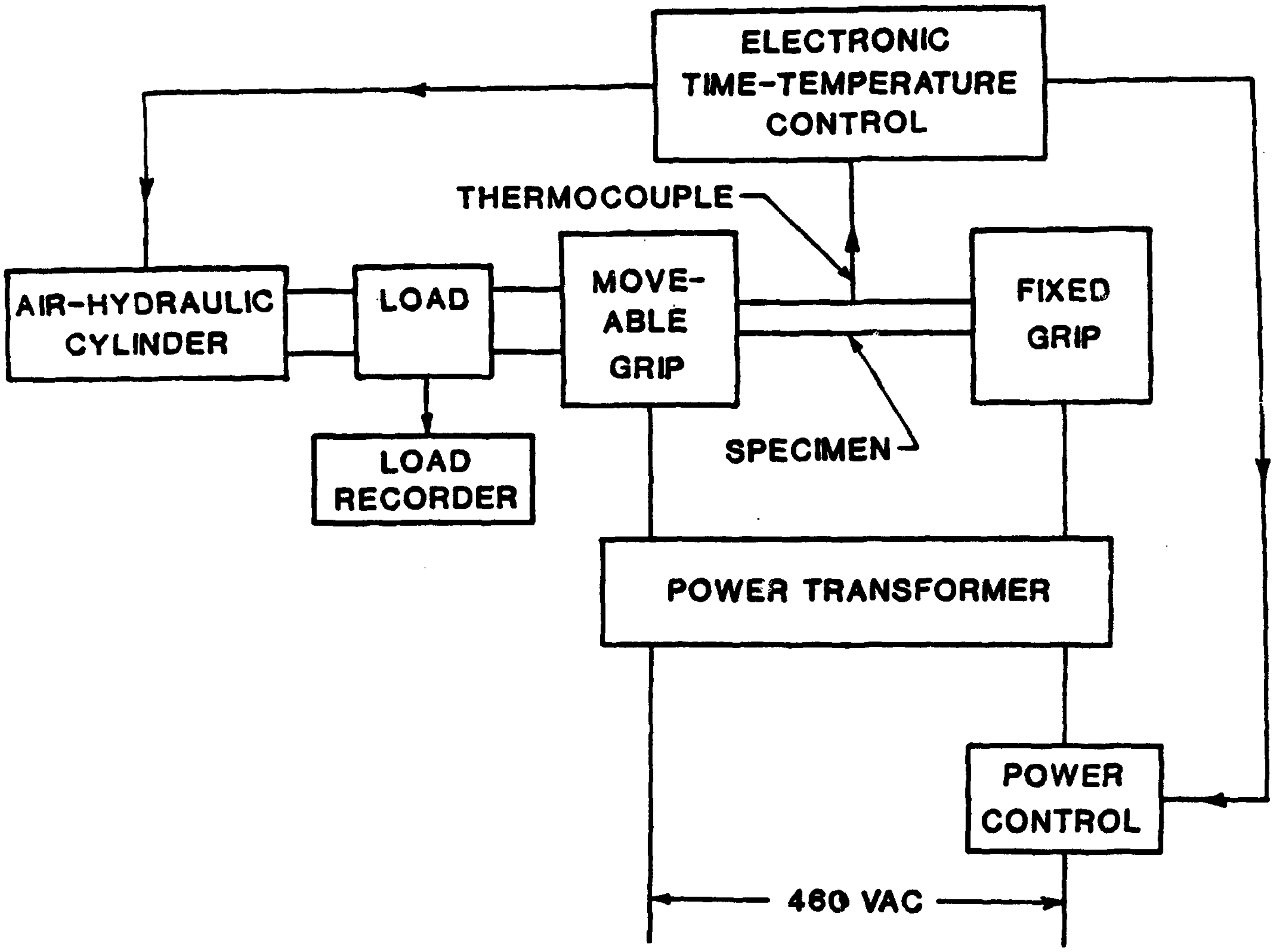


Figure 13. Schematic of the Gleeble apparatus.

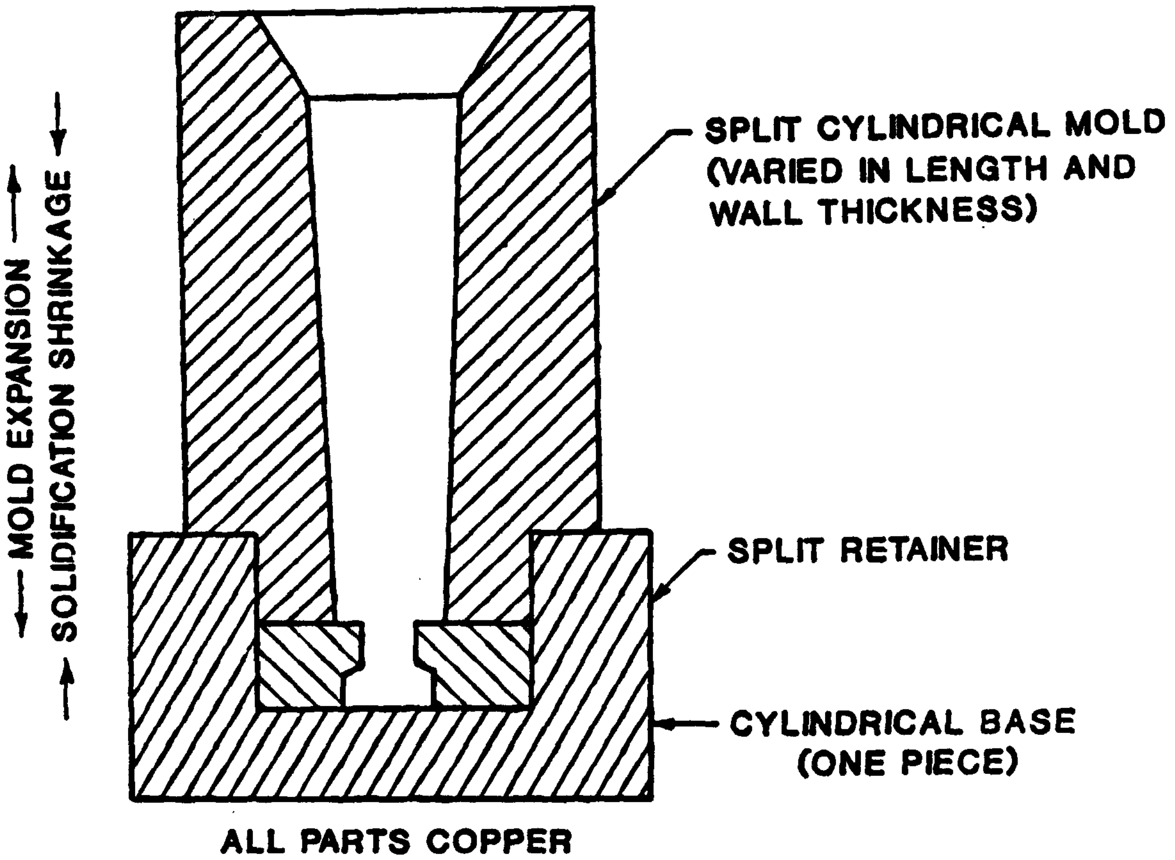


Figure 14. Schematic of the cast-pin-tear test.

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